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# Time-integrated measurements of $\gamma$ at the Tevatron and prospects

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The measurement of CP-violating asymmetries and branching ratios of  $B \rightarrow DK$  modes allows a theoretically-clean extraction of the CKM angle  $\gamma$ . We report recent CDF measurements with Cabibbo suppressed ( $\pi\pi$ ,  $KK$ ) or doubly Cabibbo suppressed ( $K^+\pi^-$ )  $D$  decays. These measurements are performed for the first time in hadron collisions.

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# 1 Introduction

Using  $B \rightarrow DK$  decays  $\gamma$  could be extracted by exploiting the interference between the tree amplitudes of the  $b \rightarrow c\bar{u}s$  and  $b \rightarrow u\bar{c}s$  processes. In Fig. 1 the diagrams of these processes are shown, on the left the  $B^- \rightarrow D^0 K^-$  ( $b \rightarrow c\bar{u}s$ ) and on the right the  $B^- \rightarrow \bar{D}^0 K^-$  ( $b \rightarrow u\bar{c}s$ ).  $\gamma$  is the relative weak phase between the two diagrams, and in principle can be probed by measuring CP-violating effects in B-decays where the two amplitudes interfere. This can be obtained in several ways, using different choices of  $D$  decay channels [1, 2, 3].

The precision of current experimental data [4] is still far from theoretical uncertainties and is statistics-limited, so the current knowledge of  $\gamma$  can be significantly improved by additional experimental measurements.

All mentioned methods for extracting  $\gamma$  from  $B \rightarrow DK$  modes require no tagging or time-dependent measurements, and many of them only involve charged particles in the final state. They are therefore particularly well-suited to hadron collider environment, where the large production can be exploited. The use of specialized trigger based on online detection of secondary decay vertexes (SVT trigger [5]) allow the selection of pure B meson samples.

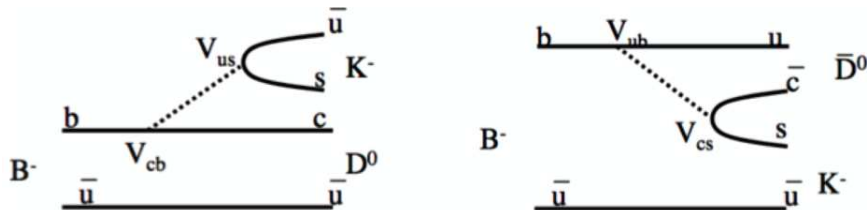


Figure 1: Diagrams contributing to  $B \rightarrow DK$  and related modes. The diagram on the left proceeds via  $V_{cb}$  transition, while the diagram on the right proceeds via  $V_{ub}$  transition and it is color suppressed.

## 2 Atwood-Dunietz-Soni method

We report the first measurement of branching ratios and CP asymmetries of  $B \rightarrow D_{DCS}K$  modes performed in hadron collisions, based on an integrated luminosity of  $5 \text{ fb}^{-1}$  collected by CDF. Events where the  $D$  meson decays to the flavor specific mode  $K^-\pi^+$  ( $D_{CF}$ ) or the doubly Cabibbo suppressed mode  $K^+\pi^-$  ( $D_{DCS}$ ) are reconstructed.

From these modes, the following observables can be defined [2]:

$$R_{ADS} = \frac{\mathcal{B}(B^- \rightarrow [K^+\pi^-]_D K^-) + \mathcal{B}(B^+ \rightarrow [K^-\pi^+]_D K^+)}{\mathcal{B}(B^- \rightarrow [K^-\pi^+]_D K^-) + \mathcal{B}(B^+ \rightarrow [K^+\pi^-]_D K^+)} \quad (1)$$

$$A_{ADS} = \frac{\mathcal{B}(B^- \rightarrow [K^+\pi^-]_D K^-) - \mathcal{B}(B^+ \rightarrow [K^-\pi^+]_D K^+)}{\mathcal{B}(B^- \rightarrow [K^+\pi^-]_D K^-) + \mathcal{B}(B^+ \rightarrow [K^-\pi^+]_D K^+)}. \quad (2)$$

These quantities are related to the CKM angle  $\gamma$  by the equations [2]  $R_{ADS} = r_D^2 + r_B^2 + 2r_D r_B \cos \gamma \cos(\delta_B + \delta_D)$  and  $A_{ADS} = 2r_D r_B \sin \gamma \sin(\delta_B + \delta_D)/R_{ADS}$ , where  $r_B$  is the magnitude of the ratio of the amplitudes of the processes  $B^- \rightarrow \bar{D}^0 K^-$  and  $B^- \rightarrow D^0 K^-$ , and  $\delta_B$  is their relative strong phase;  $r_D$  is the magnitude of the ratio of the amplitudes of the processes  $D^0 \rightarrow K^-\pi^+$  and  $D^0 \rightarrow K^+\pi^-$ , and  $\delta_D$  is their relative strong phase. We measure  $R_{ADS}$  and  $A_{ADS}$  also for the  $B \rightarrow D_{DCS}\pi$  decay mode because also for this mode sizeable asymmetries may be found [4].

The invariant mass distributions of CF and DCS modes, with a nominal pion mass assignment to the track from  $B$ , are reported in Fig. 2 where an obvious CF signal is visible, while the DCS signal appears to be buried in the combinatorial background. Due to the smallness of the DCS branching ratio (0.3% of the CF rate), the main issue for this analysis is the suppression of the combinatorial background.

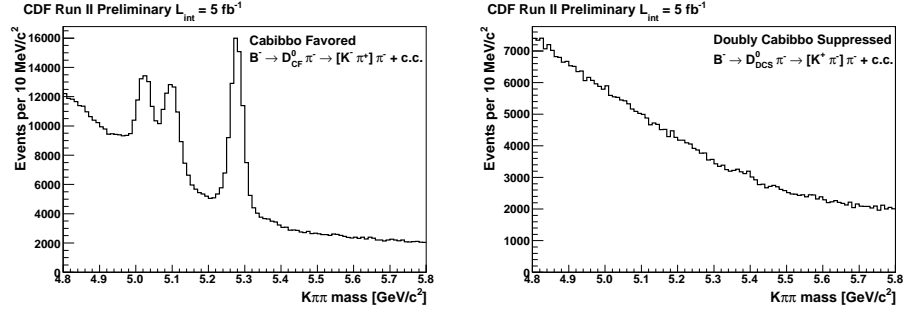


Figure 2: Invariant mass distributions of  $B \rightarrow Dh$  candidates for each reconstructed decay mode. The pion mass is assigned to the track from the  $B$  decay.

We performed a cuts optimization focused on finding a signal of the  $B \rightarrow D_{DCS}\pi$  mode. Since the  $B \rightarrow D_{CF}\pi$  mode has the same topology of the  $DCS$  one, we did the optimization using signal (S) and background (B) from the CF mode. We maximized the figure of merit  $S/(1.5 + \sqrt{B})$  [6]. The variables used in the optimization and the threshold values for all the requirements are described in [7]. The resulting invariant mass distributions of CF and DCS modes are reported in Fig. 3 where the combinatorial background is almost reduced to zero and an indication of the DCS peak is now visible.

The dominant physics backgrounds for the DCS mode are  $B^- \rightarrow D^0 \pi^-$ , with  $D^0 \rightarrow X$ ;  $B^- \rightarrow D^0 K^-$ , with  $D^0 \rightarrow X$ ;  $B^- \rightarrow D^{*0} K^-$ , with  $D^{*0} \rightarrow D^0 \gamma / \pi^0$ ;

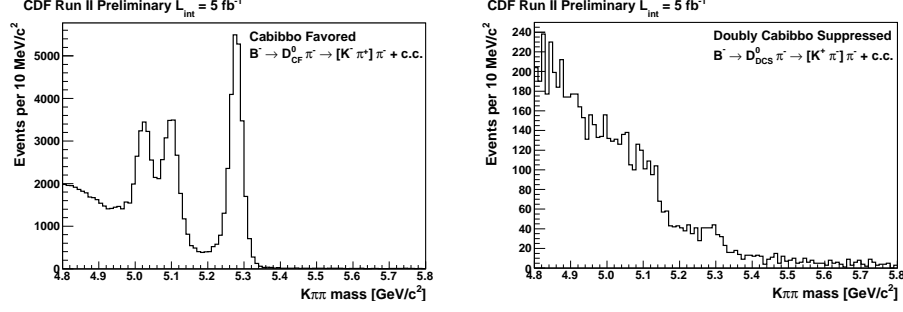


Figure 3: Invariant mass distributions of  $B \rightarrow Dh$  candidates for each reconstructed decay mode after the cuts optimization. The pion mass is assigned to the track from the  $B$  decay.

$B^- \rightarrow K^- \pi^+ \pi^-$  and  $B^0 \rightarrow D_0^{*-} e^+ \nu_e$  as determined by a study on CDF simulation described in [7].

An unbinned likelihood fit, exploiting mass and particle identification information provided by the specific ionization ( $dE/dx$ ) in the CDF drift chamber, is performed to separate the  $B \rightarrow DK$  contributions from the  $B \rightarrow D\pi$  signals, from the combinatorial background and from the physics backgrounds.

Fig. 4 shows the DCS invariant mass distributions separated in charge. We obtained  $34 \pm 14$   $B \rightarrow D_{DCS}K$  and  $73 \pm 16$   $B \rightarrow D_{DCS}\pi$  signal events.

We measured the asymmetries  $A_{ADS}(K) = -0.63 \pm 0.40(\text{stat}) \pm 0.23(\text{syst})$  and  $A_{ADS}(\pi) = 0.22 \pm 0.18(\text{stat}) \pm 0.06(\text{syst})$  and the ratios of doubly Cabibbo suppressed mode to flavor eigenstate  $R_{ADS}(K) = [22.5 \pm 8.4(\text{stat}) \pm 7.9(\text{syst})] \cdot 10^{-3}$  and  $R_{ADS}(\pi) = [4.1 \pm 0.8(\text{stat}) \pm 0.4(\text{syst})] \cdot 10^{-3}$ .

These quantities are measured for the first time in hadron collisions. The results are in agreement with existing measurements performed at  $\Upsilon(4S)$  resonance [4, 8].

### 3 Gronau-London-Wiler method

We report the first measurement of branching ratios and CP asymmetries of  $B \rightarrow D_{CP+}K$  modes performed in hadron collisions, based on an integrated luminosity of  $1 \text{ fb}^{-1}$  collected by CDF [9]. Events where the  $D$  meson decays to the flavor specific mode  $K^- \pi^+$ , or one of the CP-even modes  $K^- K^+$  and  $\pi^- \pi^+$  are reconstructed. From these modes, the following observables can be defined [1]:

$$A_{CP+} = \frac{\mathcal{B}(B^- \rightarrow D_{CP+}K^-) - \mathcal{B}(B^+ \rightarrow D_{CP+}K^+)}{\mathcal{B}(B^- \rightarrow D_{CP+}K^-) + \mathcal{B}(B^+ \rightarrow D_{CP+}K^+)}, \quad (3)$$

$$R_{CP+} = 2 \frac{\mathcal{B}(B^- \rightarrow D_{CP+}K^-) + \mathcal{B}(B^+ \rightarrow D_{CP+}K^+)}{\mathcal{B}(B^- \rightarrow D_{CF}K^-) + \mathcal{B}(B^+ \rightarrow \overline{D}_{CF}K^+)}. \quad (4)$$

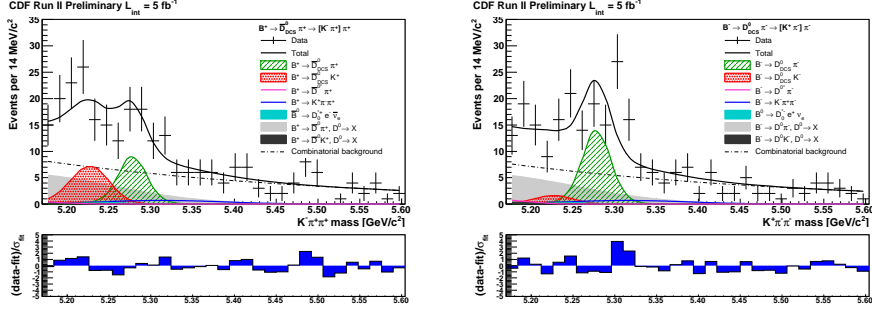


Figure 4: Left: Invariant mass distributions of  $B^+ \rightarrow \bar{D}_{CS} h^+$  candidates. Right: Invariant mass distributions of  $B^- \rightarrow D_{CS} h^-$  candidates. The pion mass is assigned to the track from the  $B$  decay. The projections of the likelihood fit are overlaid.

These quantities are related to the CKM angle  $\gamma$  by the equations [1]  $R_{CP+} = 1 + r_B^2 + 2r_B \cos \delta_B \cos \gamma$  and  $A_{CP+} = 2r_B \sin \delta_B \sin \gamma / R_{CP+}$ . For every  $B \rightarrow Dh$  candidate, a nominal invariant mass is evaluated by assigning the pion mass to the particle  $h$  coming from the  $B$  decay. The distributions obtained for the three modes of interest (where  $D \rightarrow K\pi$ ,  $KK$  or  $\pi\pi$ ) are reported in Fig. 5; a clear  $B \rightarrow D\pi$  signal is seen in each. Events from  $B \rightarrow DK$  decays are expected to form much smaller and wider peaks in these plots, located about  $50 \text{ MeV}/c^2$  below the  $B \rightarrow D\pi$  peaks, and as such cannot be resolved. The dominant backgrounds are combinatorial background and mis-reconstructed physics background such as  $B \rightarrow D^{*0}\pi$  decay, and in the  $D \rightarrow KK$  final state, the non resonant  $B \rightarrow KKK$  decay, as determined by a study on CDF simulation. An unbinned likelihood fit, exploiting kinematic and particle identification information provided by the  $dE/dx$ , is performed to statistically separate the  $B \rightarrow DK$  contributions from the  $B \rightarrow D\pi$  signals, from the combinatorial background and from the physics backgrounds.

We obtained around 90  $B \rightarrow D_{CP+}K$  and we measured the double ratio of  $CP$ -even to flavor eigenstate branching fractions  $R_{CP+} = 1.30 \pm 0.24(\text{stat}) \pm 0.12(\text{syst})$  and the direct  $CP$  asymmetry  $A_{CP+} = 0.39 \pm 0.17(\text{stat}) \pm 0.04(\text{syst})$ . These results are in agreement with previous measurements from  $\Upsilon(4S)$  decays [10, 11].

## 4 Conclusions

CDF performed the first measurement of  $A_{ADS}$  and  $R_{ADS}$  at a hadron collider using a luminosity of  $5 \text{ fb}^{-1}$ . This supplements the recently published first GLW analysis in hadron collisions [9] within a CDF global program to measure  $\gamma$  angle from tree-dominated processes. At the moment we recorded  $8 \text{ fb}^{-1}$  and we will expect around  $10\text{-}12 \text{ fb}^{-1}$  by the end of 2011. CDF has demonstrated the feasibility of these mea-

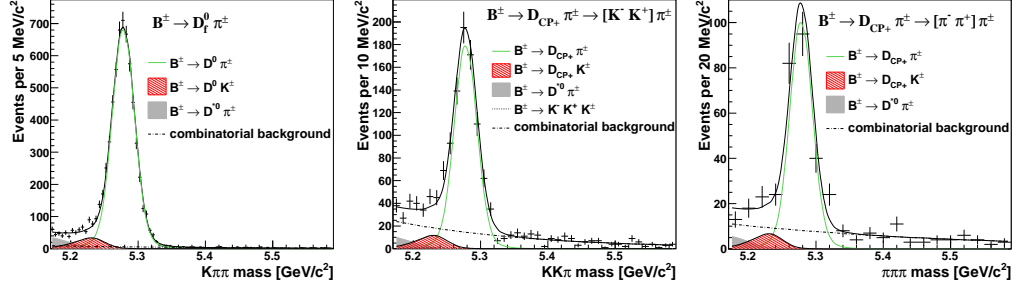


Figure 5: Invariant mass distributions of  $B \rightarrow Dh$  candidates for each reconstructed decay mode. The pion mass is assigned to the track from the  $B$  decay. The projections of the likelihood fit are overlaid for each mode.

surements at a hadron collider and will obtain interesting and competitive results in the near future.

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